Observation of magnetic domains using a reflection-mode scanning near-field optical microscope

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It is demonstrated that it is possible to image magnetic domains with a resolution of better than 60 nm with the Kerr effect in a reflection-mode scanning near-field optical microscope. Images taken of tracks of thermomagnetically prewritten bits in a Co/Pt multilayer structure magnetized out-of plane showed optical features in a track pattern whose appearance was determined by the position of an analyzer in front of the photomultiplier tube. These features were not apparent in the topography, showing this to be a purely magneto-optic effect. © *1997 American Institute of Physics.* [S0003-6951(97)01310-7]

As data densities in magnetic storage devices become higher, there is an ever-increasing need to develop a means of observing the domain structure of smaller and smaller size, in order to know how to improve the devices' efficiency. There are currently a number of different techniques used for imaging domains, including the Bitter method,[1] Lorentz-mode transmission electron microscopy,[2] scanning electron microscopy with polarization and analysis,[3] and magnetic force microscopy (MFM).[4]

Recently, the use of magneto-optical and phase-change recording media have gained in importance. Magneto-optical contrast based on the Faraday effect is often not practical as the recording media are usually opaque. Therefore, use is made of the Kerr effect to determine the magnetization state of each bit. Resolution in Kerr microscopy is limited by diffraction.[5] With green light, and an oil-immersion lens, the limit will be of the order 250 nm. The writing of bits as small as 200 nm has been successfully demonstrated with a scanning tunneling microscope, but this still requires a separate imaging technique to then read the bits.[6] The writing mechanism consists of locally heating the sample to either the compensation point, or the Curie temperature usually with a focused laser pulse, while applying a field marginally below the coercive field, in the opposite direction to that of the sample's magnetization. This enables the magnetization of the locally heated area to switch to the direction of the applied field.

The application of scanning near-field microscopy (SNOM) to magneto-optics was spectacularly demonstrated in 1992.[7] Images were produced of magnetic domains in a 1 μm thick Bismuth-doped yttrium–iron–garnet (YIG) sample, with a transmission-mode SNOM. Images of domains in a 30 nm thick Co–Pt multilayer, with an optical resolution of about 60 nm were also demonstrated. Using the same setup, bits as small as 60 nm were also written in the sample by increasing the power coupled into the SNOM tip, and therefore, locally heating the sample above the Curie point. Until recently, little work has been done in developing a reflection-mode, near-field Kerr microscope. Initial experiments indicated that the reflected light becomes depolarized when the SNOM tip is in close proximity to a conducting surface.[8]

Recently, there have been some promising results on imaging of domains in reflection using an unconventional type of SNOM. The principle here was to use a silver particle of diameter about 20 nm as a probe. This particle is excited with light, and as it is approached to a magnetic sample, the field of the sample influences the radiation characteristics of the particle. By monitoring the scattered light during scanning, a picture of the magnetic structure of the sample is obtained.[9,10] However, the setup used for these experiments is rather complicated, and the probe preparation using colloidal chemistry is quite an involved process. Also, this setup has no means of measuring the topographic structure of the sample.

We decided to try to obtain Kerr-effect images of magnetic domains with the most common type of SNOM: an instrument based on a fiber-type probe. Such work is of paramount importance, as it would pave the way to doing routine imaging of domains on opaque samples with a resolution of better than 100 nm.

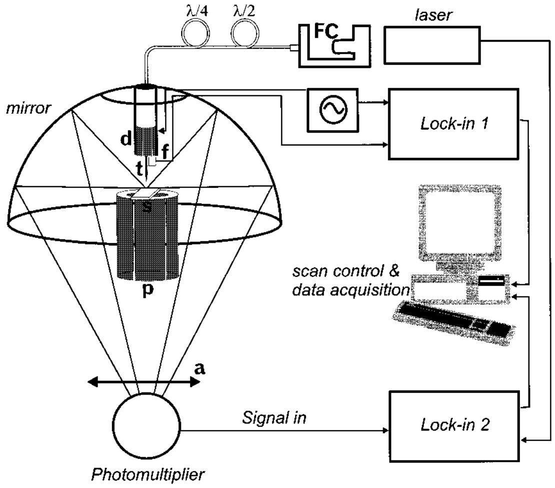

FIG. 1. Schematic of experimental setup: a: analyzer, d: dither piezo, f: shear-force detector, t: SNOM tip, s: sample, p: sample scanner piezo, and F.C.: fiber coupler.

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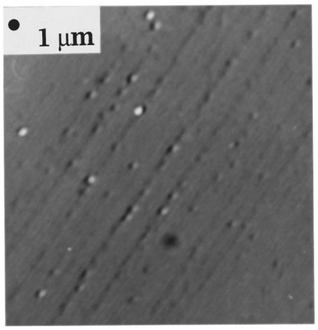

FIG. 2. Polar Kerr-effect optical microscopy image of the prewritten tracks of domains. A black dot representing a 1 μm in diameter circle is shown in the left-upper corner for comparison.

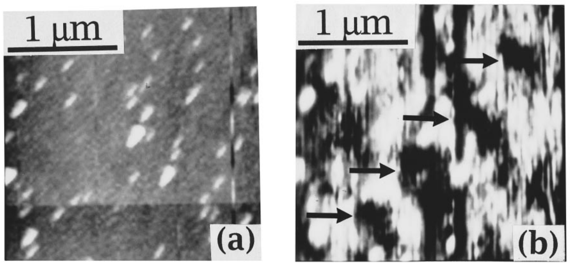

FIG. 4. (a) Shear-force and (b) SNOM images of multilayer sample. Scan size is 2.5×2.5 μm. Here, analyzer in front of PMT was at 25° to the major axis of the reflected light.

The experimental setup was as shown in Fig. 1. The light of a diode laser (10 mW, 635 nm) was coupled into a metal coated fiber probe with an aperture of about 50 nm at the end. Light emitted from this probe and reflected from the sample was collected using an elliptical mirror. The mirror was placed in such a way that the fiber tip is located at one focus and a photomultiplier detecting the optical signal at the other. This setup allows us to collect light reflected from the sample into a solid angle of $2\pi/3$. The distance between the probe and surface was maintained constant at approximately 5 nm. Distance regulation was based on the detection of the shear force between the probe and the sample surface. For the detection, the probe was oscillated by a separate piezo with an amplitude of 5–10 nm.[11,12] The sample studied here consisted of a Co/Pt multilayer, deposited on a 5 Å thick seed layer of Pt, on a glass substrate. The multilayer consisted of ten repetitions of 5 Å Co plus 5 Å Pt. It has perpendicular magnetization. The advantage of such a sample for magneto-optical experiments is that it has optical contrast but without any significant topography variations complicating the work. The polar Kerr rotation for this film, at normal incidence and a wavelength of 635 nm, is approximately 0.25°. A series of tracks of bits were thermomagnetically written in the film using a diode laser ($\lambda=670$ nm). The duration of the laser pulses was 0.24 μs. The laser power was 3 mW. Tracks of bits were recorded by pulsing the laser and moving the film at such a speed that the distance between the centers of the bits recorded was 0.8 μm. The distance between the tracks was 2 μm. The power of the laser and the focusing were adjusted to write the bits of as small size as possible. Optical Kerr microscopy analysis showed that the bits were smaller than 0.6 μm in size (Fig. 2). The tracks of the bits are clearly visible but the individual bits within the track mostly cannot be resolved. MFM analysis indicated that the bits were of the mean size of about 0.5 μm (Fig. 3).

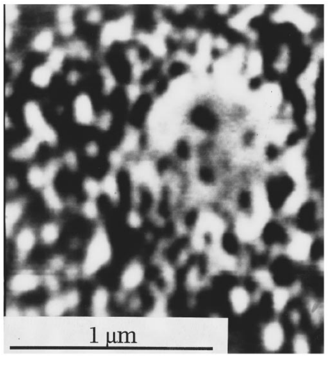

FIG. 3. MFM image showing bits and intrinsic domain structure of sample. Scan size=1.6×1.6 μm. Size of the bit shown is about 0.5–0.6 μm.

To change the state of ellipticity of the light emitted from the probe we used $\lambda/2$ and $\lambda/4$ plates installed between the laser and fiber coupler. By adjusting the angular positions of the plates, we could obtain an almost linearly polarized light at the input to the photomultiplier tube. An analyzer was installed between the mirror and the photomultiplier tube (PMT) to measure the rotation of the polarization plane. By proper choice of the positions of the $\lambda/2$ and $\lambda/4$ plates, an ellipticity ratio up to 15:1 could be readily obtained when the probe was at a distance of 2 μm or greater away from the sample. Here, all throughout the paper we define the ellipticity ratio as $E^2_{\max}/E^2_{\min}$, where $E_{\max}$ and $E_{\min}$ are the components of the electric field along and perpendicular to the main axis of the polarization ellipse of the detected light, respectively. The ellipticity ratio was found to remain virtually unchanged as the tip approached the sample from the distance of 2 μm to 5 nm. Unlike in measurements reported earlier,[8] light did not become depolarized upon the approach into the near-field distance for 70% of the tips tested. Depolarization indeed occurred for the other 30% of tips tested, for the approach to a conducting surface. These statistics are based on our measurements with about 20 different tips all fabricated, however, using the same technique.[11] Dependence of the optical signal on a particular tip is a commonplace phenomenon in near-field microscopy. It is explained by irreproducibility in the shape of the optical aperture and also the profile of the metal coating in the close vicinity to it. We believe that depolarization in some of the tips occurs upon

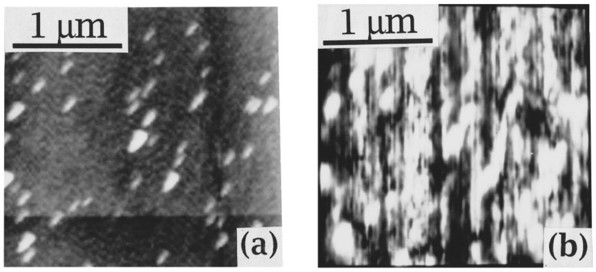

FIG. 5. (a) Shear-force and (b) SNOM images of multilayer sample. Scan size is 2.5×2.5 μm. Here, analyzer in front of PMT was at −65° to the major axis of the reflected light.

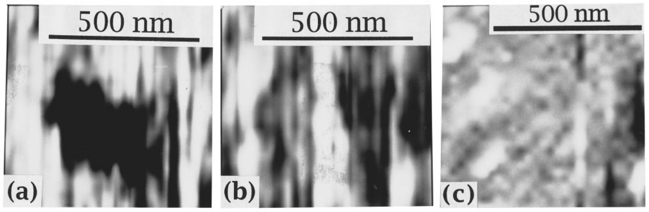

FIG. 6. Zoom in of (a) Fig. 4(b), (b) Fig. 5(b), and (c) Fig. 5(a). Scan size is 700×700 nm. The same area is shown in Figs. 1(a)–1(b).

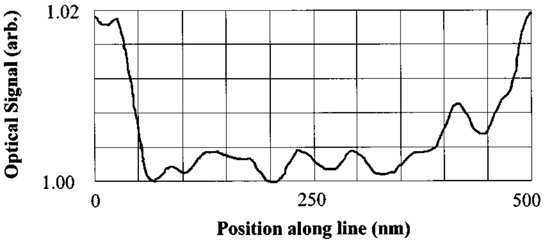

FIG. 7. Line profile through bit shown in Fig. 6(a).

the approach due to a particular shape of the tip end such that the light undergoes multiple reflections between the end face of the tip and the sample before it can escape past the tip. The number of reflections increases as the tip approaches the sample and, thus, the depolarization caused by them, too. This question is not, however, the prime subject of the present letter. What is important is that for the magneto-optic experiments described here, we used the tips with which the polarization remained unchanged upon the approach from 2 μm to 5 nm separation.

The Curie point of this sample was quite low, approximately 650 K. It is known that the SNOM tip may reach temperatures of over 500 K.[13] Consequently, there is the possibility that by scanning this sample, one may erase the bit pattern. For this reason, the optical power coupled into the probe was kept at the minimum, giving the value of the detected signal of 1.5 nW. For this signal level, a signal-to-noise ratio of about 200 with a time constant of 10 ms was obtained, thus, allowing the detection of the polarization rotation of 0.25° with a signal-to-noise ratio of 1:1.

Figure 4 shows the shear-force and SNOM images of a $2.5*2.5$ μm area of this sample. For this image, the analyzer was placed at 25° to the major axis of the elliptically polarized reflected light, of ellipticity ratio 3:1. Figure 5 shows the corresponding images for the analyzer at $-65°$ (i.e., the analyzer was rotated by 90° between scans).

It is clear that there are topographic features (protrusions) scattered over the surface, of a mean height of 10 nm. They appear bright in Figs. 4(a) and 5(a). These features are also seen in both SNOM images and they do not depend upon the polarization. However, there are several dark areas of a mean diameter of 400 nm that appear in the first SNOM image but not the second. Four such dark areas seen in Fig. 4(b) are marked by the arrows. Figure 6 shows a zoom in the same area on each SNOM image, to illustrate the point, and Fig. 7 shows a line profile through one of such areas. As these features do not show up in the topography, their appearance depends on the analyzer position, and they form a regular track at the same orientation and the same periodicity as expected. It must be concluded that these are the prewritten bits, and these images demonstrate near-field Kerr-effect magneto-optic imaging.

The contrast here is 0.02, which corresponds to a 1% change in the optical signal. For the position of the analyzer, this corresponds roughly to a rotation of 0.5°, which is made up of two opposite rotations of the bits and the surrounding film of 0.25°.

The smallest topographic features visible in the SNOM images are of the order of 50 nm. The apparent roughness of the bits as seen by SNOM is consistent with those as seen by MFM by us and also by other groups.[14,15] It is apparently due to the intrinsic domain structure of the films. The recorded domains are not circular. They have a fine structure of a characteristic dimension of 100 nm. Such a structure also appearing on the MFM image is consistent with the SNOM Kerr images.

It has been demonstrated that Kerr-effect imaging of magnetic domains is possible with an aperture-type SNOM. Images taken of a Co/Pt multilayer structure, magnetized out of plane, with tracks of prewritten bits, showed optical features in a track pattern whose appearance was determined by the position of an analyzer in front of the PMT. These features were not apparent in the topography, showing this to be a purely magneto-optic effect.

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